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模拟增温对高寒草甸物种多样性和生态系统多功能性的影响

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摘要:生物多样性与生态系统功能的关系已成为气候变化领域和生物多样性保护研究的核心议题。青藏高原是全球典型的生态脆弱区,随着全球气候变化加剧,高寒草甸生态系统的结构和功能正发生显著改变。本研究采用开顶室增温装置,综合调查植物物种多样性和多种生态系统功能,并采用均值法对生态系统多功能性进行量化分析,探讨模拟增温下物种多样性和生态系统功能及多功能性间的关系。结果表明:增温抑制地上和地下生物量的积累,且Margalef指数、Simpson指数和Shannon-weiner指数显著降低($P<0.05$)。冗余分析结果显示,生态系统多功能性与Margalef指数、Shannon-weiner指数和Simpson指数呈显著的正相关关系($P<0.05$),这些指标的提升伴随着生态系统功能的增强,其中物种丰富度相较于物种均匀度和优势度可能是更为关键的影响因子。本研究可为青藏高原高寒草甸应对全球气候变化的响应和适应机制提供重要的理论参考。

关键词:青藏高原;梯度增温;物种多样性;平均值法;生态系统多功能性

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Effects of Simulated Warming on Plant Species Diversity and Ecosystem Multifunctionality in Alpine Meadow

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Abstract: The relationship between biodiversity and ecosystem functioning has become a central issue in the fields of climate change and biodiversity conservation. The Qinghai-Tibet Plateau represents a globally typical ecologically fragile region, and with the intensification of global climate change, the structure and functioning of alpine meadow ecosystems are undergoing significant alterations. In this study, open-top chamber warming experiments were conducted to comprehensively assess plant species diversity and multiple ecosystem functions. Ecosystem multifunctionality was quantified using the averaging method to explore the relationships among simulated warming, species diversity, ecosystem functions, and multifunctionality. The results showed that warming suppressed the accumulation of aboveground and belowground biomass, while Margalef index, Simpson index, and Shannon-Weiner index decreased significantly ($P<0.05$). Redundancy analysis indicated that ecosystem multifunctionality was significantly positively correlated with Margalef index, Shannon-Weiner

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index, and Simpson index ($P < 0.05$), with improvements in these indices accompanying enhancements in ecosystem functioning. Among these, species richness appeared to be a more critical influencing factor compared with species evenness and dominance. This study provides an important theoretical reference for understanding the responses and adaptive mechanisms of alpine meadow ecosystems under global climate change on the Qinghai-Tibet Plateau.

Key words: Tibetan Plateau; Gradient warming; Species diversity; Mean method; Ecosystem multifunctionality

联合国气候变化政府间专家委员会第6次评估报告指出,自工业革命以来,大气中CO₂浓度的增加导致陆地和全球地表温度分别升高1.59℃和1.09℃^[1]。青藏高原是我国重要的生态安全屏障,同时也是生态系统演变过程中的典型生态脆弱区与气候变化响应的敏感区,随着全球气候变暖的不断加剧,其独特的地形与巨大的热力循环作用使此区域增温的速率与幅度更为显著^[2-4]。高寒草甸作为高寒地区主要的草原类型之一,对青藏高原的多种生态系统功能具有重要作用^[5]。高寒草甸区域生态系统脆弱、环境恶劣,其生态系统对全球气候变化高度敏感^[6]。因此,高寒草甸成为了揭示陆地生态系统应对气候变化机制的理想研究对象。

生态系统功能通常被定义为生态系统的过程或性质^[7],生物多样性是驱动生态系统功能的重要因素^[8]。然而,全球环境变化和人类活动加速了生物多样性的丧失,并最终影响生态系统功能^[9]。早期关于生物多样性和生态系统功能的研究仅针对单个生态功能进行,然而,生态系统功能本质上是多维的,仅考虑单一功能存在局限性,其他潜在的生态功能易被忽视^[10-13]。随着探索的不断深入,Sanderson等提出了“生态系统多功能性”的定义^[14],Hector和Bagchi将生态系统多功能性描述为生态系统同时维持和提供多种服务与功能的能力^[10]。同时,生物多样性与生态系统功能间关系的协同性及其适应性、生物多样性对单一功能与对多个生态系统功能的响应是否一致等问题成为多样性与生态系统功能研究新的热点方向^[15-17]。

传统的生物多样性与生态系统多功能性的研究多集中在物种多样性与生态系统多功能性的关系上^[18]。目前研究已提出生态系统多功能性的量化方法包括单阈值法、均值法、多阈值法、单功能法、功能-物种替代法、多元模型法等^[19],而均值法因其计算简单、结果直观被广泛应用于量化生态系统多功能性,占已发表相关论文总数的41%以上^[20]。在高寒草地生态系统研究中,许多学者采用均值法评估多功能性,以揭示不同处理或环境梯度下生态系统多功能性的整体变化^[21-23]。气候因素可以对生态

系统的多功能性产生直接影响,且环境变化可以通过改变植物群落多样性来调节生态系统的多功能性^[24]。Zhao等对生态系统多功能性的研究结果表明,试验增温对高寒草甸生态系统多功能性的影响不显著^[25]。但也有研究指出,增温处理下高寒草甸生态系统多功能呈增加趋势^[26],然而温度升高也会导致草原土壤养分有效性下降,从而导致生态系统多功能性下降^[27]。综上,不同生态系统类型下的生态系统多功能性,由于其量化指标的选取、计算方法以及对地上和地下功能侧重等的不一致使其结果存在不确定性。

因此,本研究基于野外模拟增温控制试验平台,采用开顶室增温装置,系统测定了高寒草甸地上和地下生产力^[28]、养分循环和固存能力^[29-31]、土壤涵养水分能力^[29]等12个生态系统功能指标,采用平均值法量化生态系统多功能性,分析模拟增温对高寒草甸生物多样性和生态系统多功能性的影响,揭示模拟增温下高寒草甸植物物种多样性与生态系统多功能性间的相互关系,有助于深化对青藏高原高寒草甸响应与适应全球气候变化机理的认识。据此,本研究提出以下假设:(1)模拟增温将通过改变植物群落结构和土壤环境,显著影响高寒草甸的多项生态系统功能,但不同功能对增温的响应幅度存在差异;(2)模拟增温处理将降低植物物种多样性,从而对生态系统多功能性产生负面影响。

1 材料与方法

1.1 样地概况

本试验在海北高寒草甸研究站(37°36′47″N, 101°18′54″E)开展。研究站位于青海省海北藏族自治州门源县(图1),海拔3200~3250 m。该区域年平均气温为-1.7℃,年平均降水量约为500 mm,其中大部分集中在夏季(5—9月份),研究区域植被群落以高寒草甸为主,群落结构简单,生长季较短,生产力较低,以矮生嵩草为优势种的高寒草甸分布在山地的阳坡和山脊上^[32-33]。

1.2 样地设置与植被调查

基于 2011 年在“海北站”建立的 OTCs 模拟增温试验平台,面积为 50 m×50 m,实验共设 25 个样地,5 个温度处理,每个处理重复 5 次(图 1)。对照(CK)采用 PVC 管围成面积约 2 m²的天然草地,并在各样地之间留 2 m 的缓冲带以防相互干扰。设置不同规格(W₁,W₂,W₃,W₄)的 OTCs 实现 4 种模拟增温梯度,根据前期生长季(5—9 月份)的监测结果(表 1),4 个增温梯度增温效果明显^[34]。

在试验区域设置 0.5 m×0.5 m 样方,调查样方内植物种类、频度、盖度、密度等。完成群落调查后,将剪取的植株地上部分收集于纸袋中。在

植物群落调查的同时,利用土钻(6 cm 直径,0~10 cm,10~20 cm 和 20~30 cm 深度)取样法采集混合根样和土样。获取土壤样品后,用筛分法将根系和土壤分离并对土壤样品进行冲洗风干。土壤容重采用环刀法(100 cm³)测定,将土壤表面的植物凋落物清理干净,用环刀在 0~10 cm 的深度采集样品。之后,将植物地上部分、根系(80℃)和土壤容重样品(105℃)放入烘箱,烘干至恒重并称重记录数据。其余土样密封保存于自封袋中,以备后续土壤理化性质的测定。由于 80% 以上的土壤养分集中在表层,因此本研究采用表层土壤(0~10 cm)代表土壤养分状况。

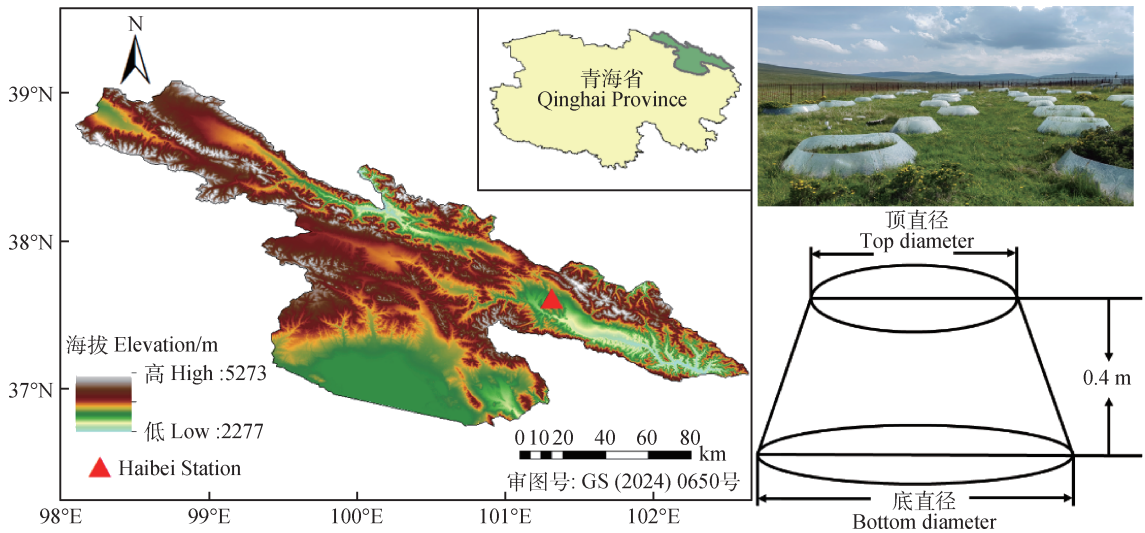


图 1 OTCs 及试验区地理位置示意图

Fig. 1 Schematic diagram of OTCs and the geographic location of the experimental site

表 1 OTC 增温设计及其微气候效应

Table 1 OTC warming design and its micro-climate effect

增温梯度 Warming gradient	顶边长度 Top side length/m	底边长度 Bottom side length/m	高度 Height/m	增温效果 Warming effect/℃	
				地上 10 cm 处空气温度	地下 10 cm 处土壤温度
				Atmospheric temperature at 10 cm above the ground	Soil temperature at 10 cm underground
W ₁	1.6	2.05	0.4	0.48	0.60
W ₂	1.3	1.75	0.4	0.60	0.98
W ₃	1.0	1.45	0.4	0.87	1.25
W ₄	0.7	1.15	0.4	1.20	1.88

1.3 生态系统功能指标测定及方法

生态系统多功能性指标的测定及方法依据前人研究^[35-37],地上生物量(Aboveground biomass AGB)和地下生物量(Belowground biomass, BGB)用烘干法测定;pH 值使用 pH 计测定;土壤湿度(Soil moisture, SM)通过温湿度仪测定;土壤容重(Bulk density, BD)用环刀法测定;利用 CHNS-analyser 分析仪测定有机碳(Soil organic carbon,

SOC)和全氮(Total nitrogen, TN)含量;土壤全碳(Total carbon, TC)含量用元素分析仪测定;利用钼锑抗比色法测定土壤全磷(Total phosphorus, TP)含量;土壤速效磷(Available phosphorus, AP)含量用 Mehlich-3 提取法测定;利用流动注射分析仪 FIAstar 5000 Analyzer 测定铵态氮(Ammonium nitrogen, NH₄⁺-N)和硝态氮(Nitrate nitrogen, NO₃⁻-N)含量。

1.4 物种多样性与生态系统多功能性计算方法

于8月中旬调查植物群落特征,计算物种重要值,选择 α -多样性的常用指数来估计群落结构的多样性^[38],公式如下:

$$IV = \frac{rh + ra + rf}{3} \quad (1)$$

$$R = S \quad (2)$$

$$H = -\sum_{i=1}^s P_i \ln(P_i) \quad (3)$$

$$H' = 1 - \sum_{i=1}^s P_i^2 \quad (4)$$

$$E = \frac{H}{\ln(S)} \quad (5)$$

$$P_i = \frac{IV_i}{IV_{\text{total}}} \quad (6)$$

其中,IV,R,H',H和E分别表示重要值、Margalef指数、Simpson指数、Shannon-Wiener指数和Pielou指数;rh,ra,rf分别表示相对高度、多度和频度; i 表示第 i 种植物, P_i 表示第 i 种植物在每个样方中的相对重要值, S 为每个样方中植物物种的总数。

选择AGB,BGB,TC,TP,TN,SOC,AP, NH_4^+-N , NO_3^--N ,pH,BD和SM共12项生态系统功能指标来表征生态系统多功能性。采用简单且直观的平均值法量化生态系统多功能性指数,单样本Shapiro-Wilk检验结果表明TP,AP, NO_3^--N 和pH值不服从正态分布($P < 0.05$),其余8个参数均服从正态分布,因此,在计算Z分数之前将每个功能标准化到一个共同的尺度,Z分数计算公式如下:

$$Z_{ij} = (X_{ij} - \lambda_j) / \delta_j \quad (7)$$

其中, Z_{ij} 和 X_{ij} 表示样地 i 生态系统功能指标 j 的Z分数和数值, λ_j 和 δ_j 表示第 j 种生态系统功能指标在样地间的平均值和标准差。对每个样地12种指标的Z分数求取平均值记为多功能性指数(M)^[39]。计算公式如下:

$$M = \sum_j^{13} X_{ij} / 13 \quad (8)$$

1.5 数据处理

运用IBM SPSS 26.0单因素方差(One-way ANOVA)分析模拟增温对物种多样性及生态系统各功能的影响,并用Origin 2021绘图。增温梯度下物种多样性与地上和地下生物量、土壤理化性质、土壤养分循环的整体关联格局采用典型相关分析法(Canoco5.0)进行分析。对高寒草甸单一生态系统功能与物种多样性之间的关系进行Pearson相关

分析,并用一元线性回归量化物种多样性和生态系统多功能性的关系。

2 结果与分析

2.1 高寒草甸物种多样性对模拟梯度增温的响应

不同增温处理导致Margalef指数、Shannon-Wiener指数和Simpson指数相较于对照均有所下降,其中Margalef指数在 W_3 和 W_4 处理下显著降低($P < 0.05$)。与对照相比,Pielou指数在各增温处理下均有所上升, W_3 处理下升幅显著($P < 0.05$)。Simpson指数和Shannon-Wiener指数在各处理间差异不显著。增温会减少物种丰富度、多样性和优势度,但同时促进了物种分布的均匀化,且Margalef指数和Pielou指数对高度增温比对较低度增温响应更为敏感(图2)。

2.2 高寒草甸生态系统功能因子对模拟梯度增温的响应

与对照组相比,不同增温处理导致地上和地下生物量出现不同程度的减少,增温使地上生物量减少了16.65%~32.46%,地下生物量减少了3.80%~62.25%,其中 W_3 增温处理下的地上生物量较对照(CK)显著下降($P < 0.05$),但地下生物量均未有显著性差异。模拟增温抑制了高寒草甸地上与地下生物量的积累,增温幅度越大,这种抑制作用越明显(图3)。

与对照相比,不同增温处理下土壤全氮、全碳、有机碳和全磷含量均未表现出显著差异。土壤全氮和有机碳随着增温梯度整体有减少的变化趋势,全碳和全磷在增温梯度间没有显著的变化规律(图4)。不同梯度增温处理下,土壤速效磷、铵态氮和硝态氮含量均呈现“单峰型”的变化趋势。与对照相比, W_2 处理下土壤速效磷和硝态氮含量显著增加($P < 0.05$);与对照相比, W_1 处理下土壤铵态氮含量显著增加($P < 0.05$,图5)。适度增温提高了N和P有效性的潜力,而过高增温水平则可能抑制土壤养分的释放。

土壤pH值随增温梯度增加整体呈增加的变化趋势,且在 W_4 处理下达到显著水平($P < 0.05$)。土壤湿度在不同增温处理下均有所降低, W_3 处理下达到显著性差异($P < 0.05$)。与对照相比,土壤容重在 W_2 和 W_3 处理下显著增加($P < 0.05$,图6)。

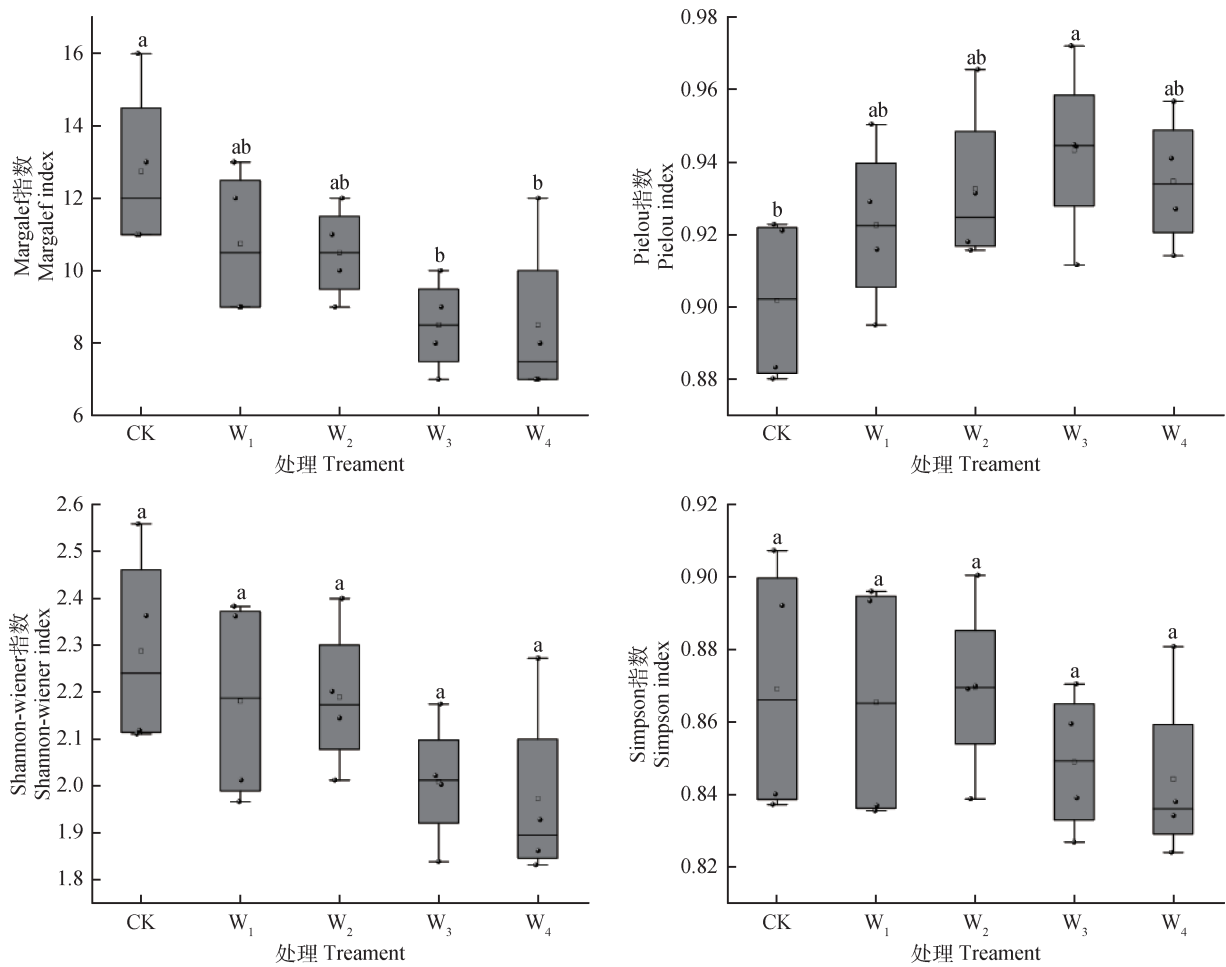


图2 模拟增温对高寒草甸物种多样性的影响

Fig. 2 Effects of simulated warming on species diversity in alpine meadows

注:图中各字母表示处理之间的显著差异($P < 0.05$)。W₁, W₂, W₃和W₄为增温梯度;CK表示对照。下同

Note: Different letters in the figure indicate significant differences among treatments ($P < 0.05$). W₁, W₂, W₃, and W₄ represent warming gradients; and CK denotes the control. The same as below

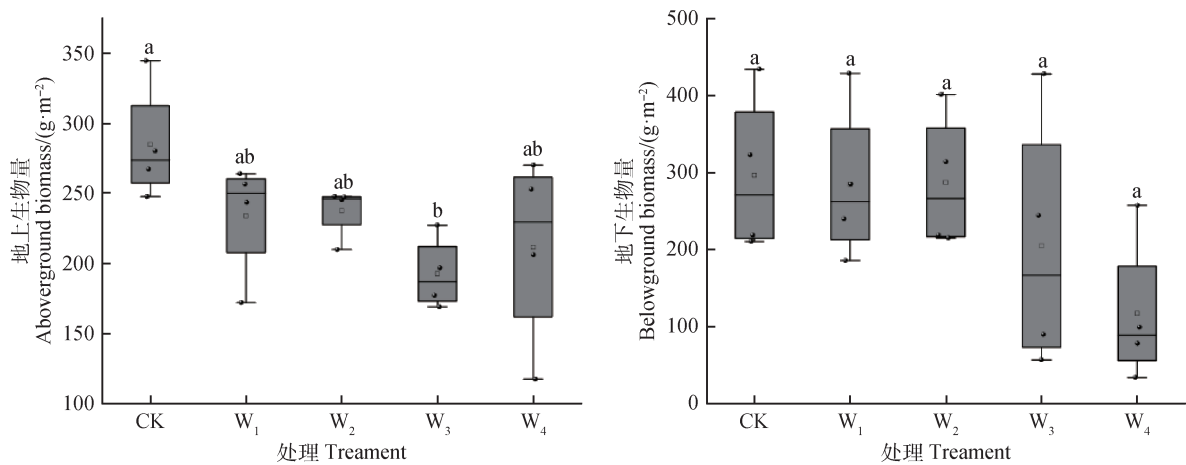


图3 模拟增温对高寒草甸地上-地下生物量的影响

Fig. 3 Effects of simulated warming on above-and belowground biomass in alpine meadows

Pearson 相关性分析结果表明(图7), TN 和 SOC 与 Margalef 指数显著正相关($P < 0.05$), TN, TP, SOC 与 Shannon-Wiener 指数显著正相关($P <$

0.05), TP 和 SOC 与 Simpson 指数显著正相关($P < 0.05$), Pielou 指数与土壤养分没有显著相关性,但会受 BD 和 TC 的影响。RDA 结果显示(图8),排列

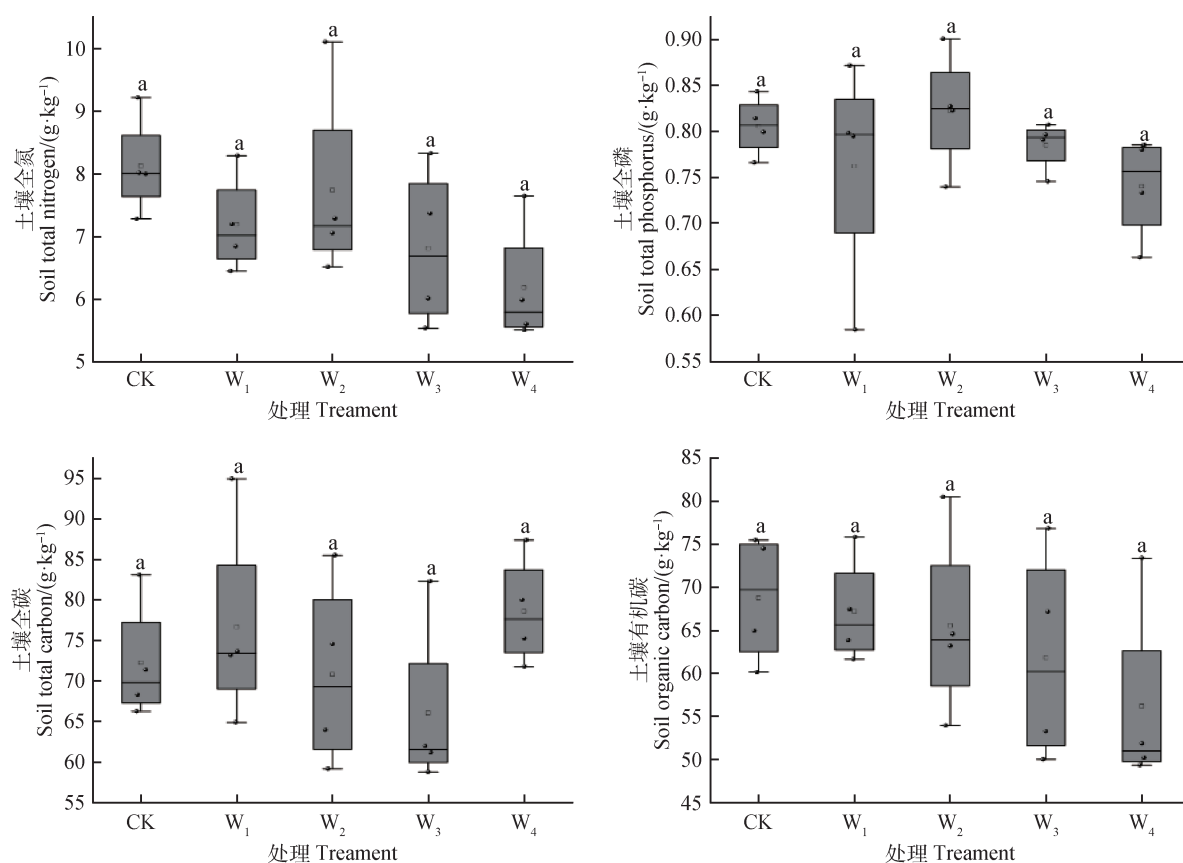


图 4 模拟增温对高寒草甸土壤碳、氮、磷的影响

Fig. 4 Effects of simulated warming on soil carbon, nitrogen, and phosphorus in alpine meadows

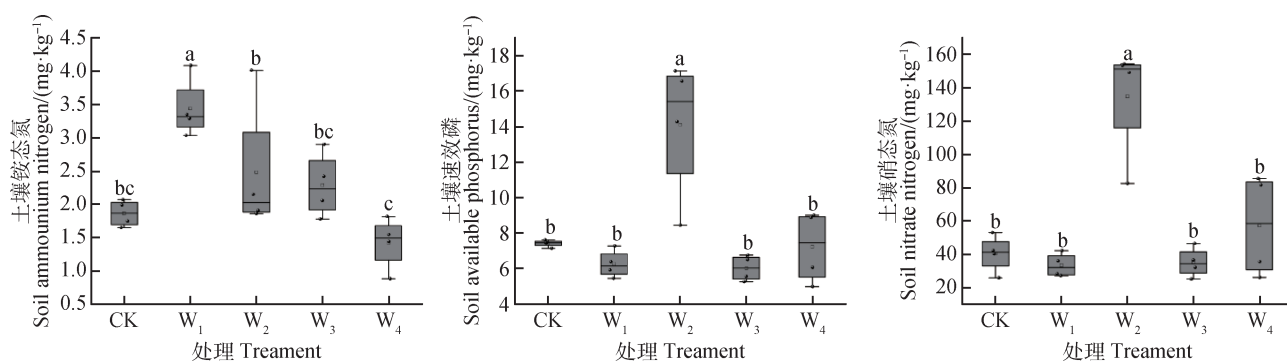


图 5 模拟增温对高寒草甸土壤速效养分的影响

Fig. 5 Effects of simulated warming on soil available nutrients in alpine meadows

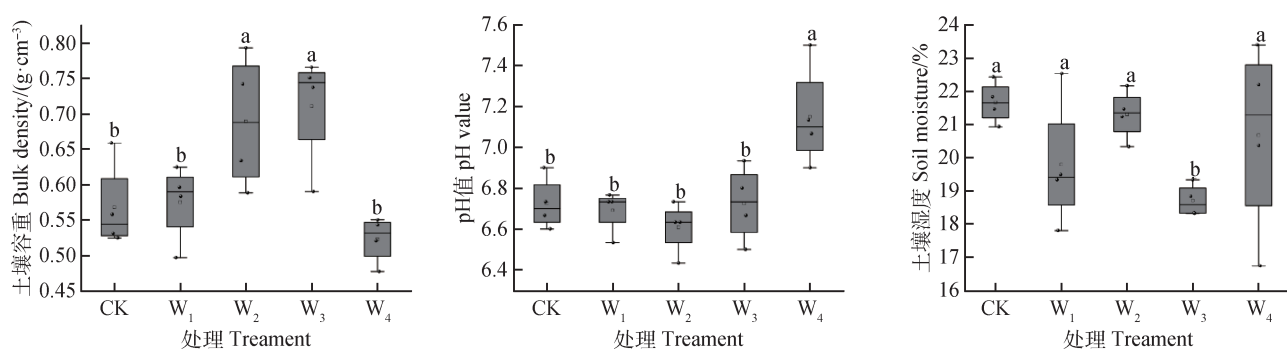


图 6 模拟增温对高寒草甸土壤涵养水分的影响

Fig. 6 Effects of simulated warming on soil water retention in alpine meadows

检验在所有典型排序轴上均具有显著性 ($P < 0.05$), 第一排序轴解释率为 72.70%, 第二排序轴解释率为 0.06%, 两个排序轴共解释了 72.76% 的变异, 表明模拟增温条件下, 各生态系统功能指标能较好地解释植物物种多样性的变化。

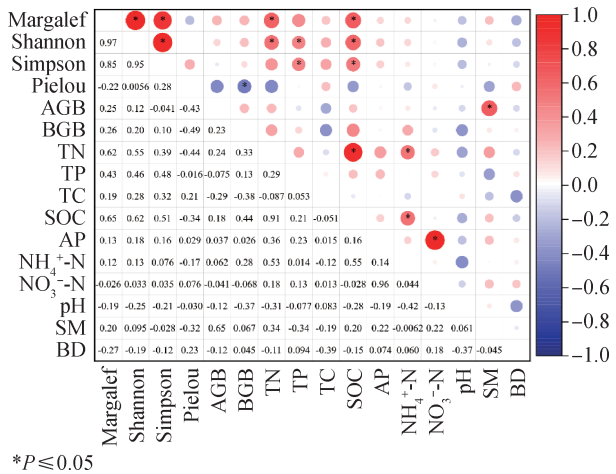


图 7 模拟增温下高寒草甸物种多样性与生态系统功能指标的相关分析

Fig. 7 Relationship analysis of plant species diversity and ecosystem function variables in alpine meadows subjected to simulated warming

注: Margalef, Shannon, Simpson, Pielou, AGB, BGB, pH, BD, SM, SOC, TP, TC, AP, $\text{NH}_4^+\text{-N}$, $\text{NO}_3^-\text{-N}$ 分别表示 Margalef 指数、Shannon-weiner 指数、Pielou 指数、地上生物量、地下生物量、pH 值、土壤容重、土壤湿度、土壤有机碳、土壤全磷、土壤全碳、土壤速效磷、土壤全氮、土壤铵态氮、土壤硝态氮含量。*代表差异显著 ($P < 0.05$)。下同

Note: Margalef, Shannon, Simpson, Pielou, AGB, BGB, pH, BD, SM, SOC, TP, TC, AP, $\text{NH}_4^+\text{-N}$, and $\text{NO}_3^-\text{-N}$ represent the Margalef index, Shannon-Wiener index, Pielou index, aboveground biomass, belowground biomass, pH, soil bulk density, soil moisture, soil organic carbon, total phosphorus, total carbon, available phosphorus, total nitrogen, ammonium nitrogen, and nitrate nitrogen content, respectively. * indicates significant difference ($P < 0.05$). The same as below

2.3 模拟增温下物种多样性和生态系统多功能性之间的关系

生态系统多功能性指数在不同增温梯度处理下的变化如表 2 所示, 生态系统多功能性在梯度增温下整体呈先升高后降低的趋势。与对照相比, 生态系统多功能性在 W_2 处理下达到最高值, W_3 和 W_4

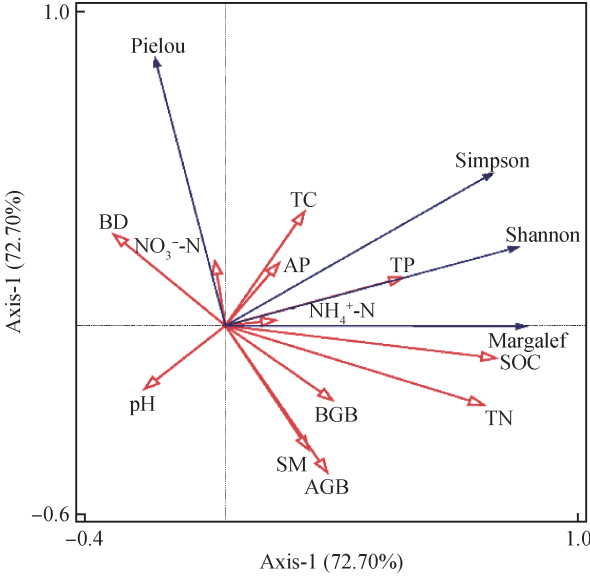


图 8 模拟增温下高寒草甸物种多样性与生态系统功能指标的冗余分析

Fig. 8 Redundancy analysis of species diversity and ecosystem functional indicators in alpine meadows under simulated warming

处理下显著降低 ($P < 0.05$)。回归分析结果表明, 模拟增温处理下, 生态系统多功能性和 Simpson 指数呈显著的正相关关系 ($P < 0.05$), 与 Margalef 指数、Shannon-weiner 指数呈极显著的正相关 ($P < 0.01$), 而 Pielou 指数与多功能性无显著相关性。单因素拟合分析显示, Margalef 指数对生态系统多功能性的解释力最强, 解释量达 34.2% ($P < 0.01$); Shannon-weiner 指数次之, 解释量为 33% ($P < 0.01$), Simpson 指数解释量最低, 为 20.5% ($P < 0.05$, 图 9)。

表 2 生态系统多功能性指数在不同增温梯度下的变化
Table 2 Changes in the ecosystem multifunctionality index under different warming treatments

增温梯度 Warming gradient	生态系统多功能性指数 Ecosystem multifunctionality index
CK	0.20 ± 0.04^a
W_1	0.11 ± 0.06^{ab}
W_2	0.55 ± 0.28^a
W_3	-0.37 ± 0.23^{bc}
W_4	-0.49 ± 0.14^c

注: 表中各字母表示处理之间的显著差异 ($P < 0.05$)
Note: Different letters in the table indicate significant differences between treatments ($P < 0.05$)

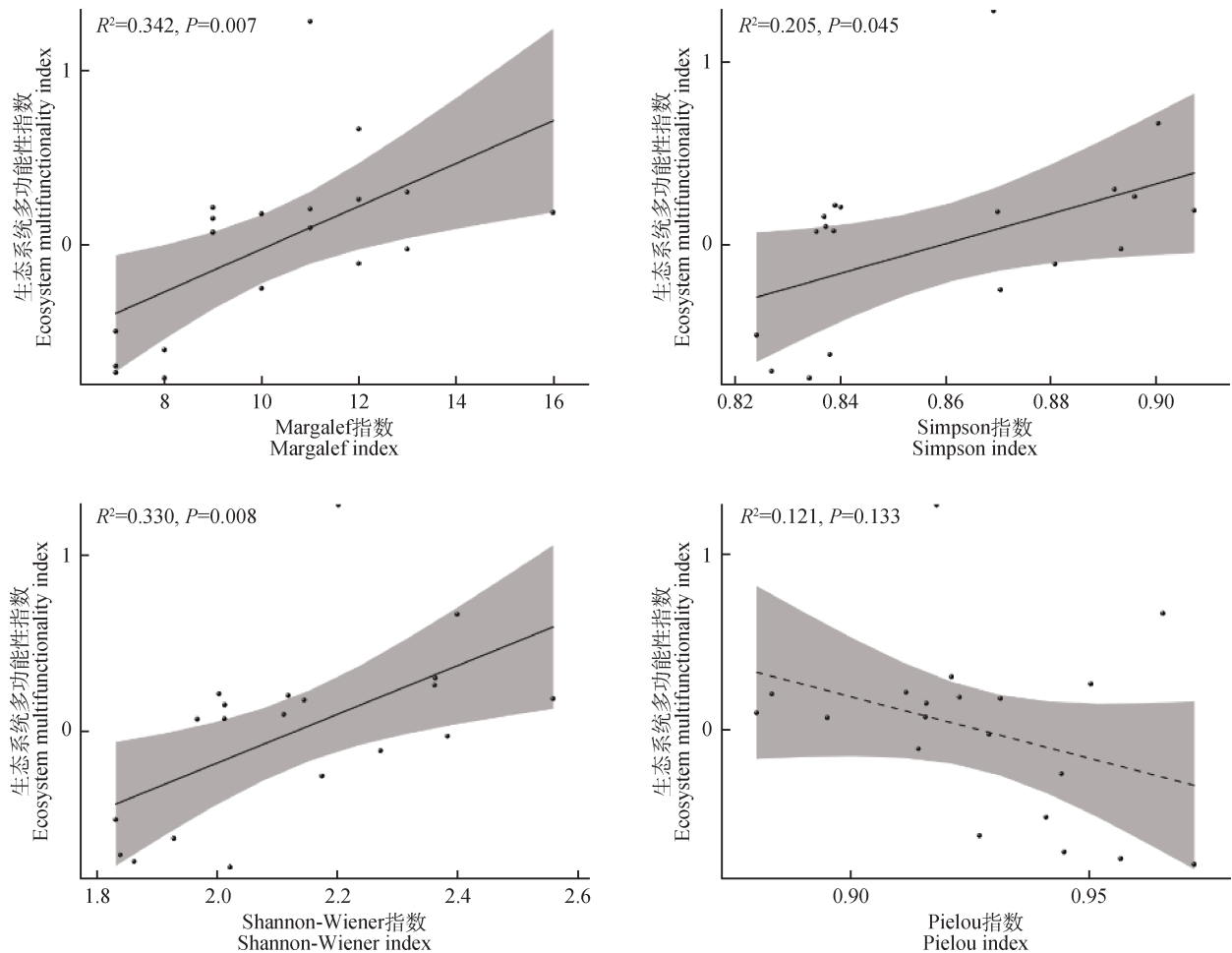


图9 模拟增温下高寒草甸物种多样性与生态系统多功能性关系

Fig. 9 Association of species diversity with ecosystem multifunctionality in alpine meadows under simulated warming

3 讨论

植物物种多样性是影响群落功能复杂性和稳定性的重要因素。多数研究表明,短期增温促进物种多样性的增加,但未达显著水平^[40-42]。一项为期14年的增温实验结果显示,物种多样性在第八年开始下降^[43]。植物群落对增温响应存在差异,这主要是由于长期增温的响应可能受水分和养分的限制^[44]。本研究表明,模拟增温下 Margalef 指数、Shannon-Wiener 指数和 Simpson 指数均有所下降,且 Shannon-Wiener 指数和 Simpson 指数未达到显著性水平。因此,增温降低了高寒草甸群落的物种丰富度、多样性和优势度。这一变化可能与增温引起的热胁迫和干旱胁迫共同作用有关,由于不同植物物种对温度的敏感性差异,从而导致某些抗温、抗逆能力较差的植物物种超过了适应范围的阈值,使物种优势度下降和物种丧失,最终导致群落结构发生变化^[45]。相反, Pielou 指数在增温处理下略有

增加,这与徐满厚等研究结果相似^[41]。增温虽导致优势种衰退、物种数量减少,但同时促进了群落内物种分布的均匀化,随着部分优势种减少,群落内的竞争关系可能得到缓解,使得次优势种或耐逆性较强的物种能够更均衡地共存。

温度是影响地球化学循环和土壤养分的关键因素^[46],在一定程度上促进生态系统的多功能性。有研究发现,增温后高寒草甸群落全氮含量和土壤有机碳含量均降低,且土壤有机碳含量未达到显著性差异^[47-49],与本实验研究相符。这主要与增温持续时间较长及升温幅度较大有关^[50]。向雪梅等研究得出不同结论,增温显著增加高寒草甸全氮含量,可能是温度升高增强了土壤微生物活性,促进固氮过程和有机质的分解,从而提高了土壤中氮的积累^[51]。同时,土壤养分作为植物生长发育必需的物质基础,长期(16年)观测结果表明,增温使速效磷含量增加^[49]。Wang 等研究指出,青藏高原高寒草甸短期和长期增温均显著增加了 NH_4^+-N 含量^[52],提高了 N 和 P 有效

性的潜力,这与本实验研究结果一致。因此,在温度升高的条件下,高寒草甸土壤养分有效性(如氮、磷)的增加驱动地上植物生产,增强了植物的新陈代谢和生长,使得植物群落结构发生变化,进而改变植物物种多样性^[53],且物种多样性较高的群落能够增强生产力和土壤养分循环等生态系统功能^[54-55]。

生物多样性并非驱动生态系统多功能性的唯一因素,气候与非生物因子同样在生态系统功能中发挥重要作用^[56]。有研究表明,无论是短期(2年)还是长期(10年)增温高寒草甸的土壤湿度都是降低的^[52],与本实验研究结果一致。不同类型草地的土壤pH值和土壤容重对气候变化的响应不同,如增温对高寒草甸土壤pH值未产生显著影响^[57-58],增温20年后,土壤pH值达到显著水平^[59],但高寒草地pH值随气温的升高而降低^[60]。本试验研究发现,土壤pH值总体呈增加的趋势,这一现象可归因于不同草地类型在植物群落组成和生产力、根系分泌物、土壤微生物群落结构、土壤湿度及养分可利用性等方面对气候变化的响应存在差异^[61]。而土壤容重的变化不仅受土壤性质的影响,还受到土壤理化特性(如深度、pH值及有机碳含量)等的影响^[62]。综上,土壤湿度、pH值、土壤容重的变化会直接或间接调控草地生态系统土壤养分和环境条件,从而对生态系统的多功能性产生影响^[63-65]。

物种多样性在调节气候因子对生态系统多功能性的影响方面发挥重要作用。本研究采用均值法计算生态系统多功能性,发现物种多样性指数与生态系统多功能性之间呈显著的协同变化关系。Dietrich等发现,植物多样性增强了生态系统多功能性抵抗力和恢复力,生态系统多功能性随植物物种丰富度的增加而增加^[66],全球旱地生态系统中生态系统多功能性与物种丰富度呈显著正相关,与本试验研究结果相符^[31]。Zhang等研究得出不同结论,模拟增温试验下高寒草甸生态系统功能未受到物种多样性显著影响,而环境因素则部分影响生态系统功能。这可能与研究区所在的高寒环境导致植被处于不饱和状态有关,当植物生物多样性未发生显著变化时,环境干扰缓解了这种未饱和状态^[67]。表明多样化程度高的植物群落提高了资源利用的互补性和效率,且不同群落之间对资源的竞争能够促进生态位分化,从而使得多样性程度较高的群落对生态系统中的空间和资源实现较高的资源利用效率,进而使生态系统多功能性维持在较高水平^[68-69]。

4 结论

本研究考虑了12个生态系统功能指标,并采用均值法量化生态系统多功能性,系统分析了物种多样性与生态系统多功能性的关系。模拟增温减少了高寒草甸物种多样性,抑制地上生物量和地下生物量的积累;适度增温可以提高土壤氮磷有效性,促进生态系统多功能性的提升,但过度增温则对生态系统多功能性具有消极影响。Margalef指数、Shannon-Weiner指数和Simpson指数与生态系统多功能性之间存在显著的协同变化关系。模拟增温处理下高寒草甸物种多样性与生态系统多功能性密切相关,物种丰富度和多样性越高,生态系统多功能性也随之增强。本研究为气候变暖下高寒草甸生态系统功能变化提供了理论依据,同时对高寒草甸生态系统的保护与管理具有启示意义。

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